SECTION 6: HIGH-VOLTAGE DC TRANSMISSION

ESE 470 – Energy Distribution Systems

Introduction

High-Voltage AC Transmission

- Power is transmitted at ***high voltage***
  - Lower current
  - Lower I^2R line losses
- Most power transmitted as ***high-voltage AC***
  - Transformers step voltages up for transmission, down at loads
  - Transformers only work for AC
- Advancement of ***power electronics*** has enabled high-voltage DC (HVDC) transmission
  - Power electronic converters can generate DC voltages of 100s of kV

HVAC Transmission – Disadvantages

- HVAC Transmission has disadvantages:
  - Reactive power consumed by transmission lines
    - Losses
  - Skin effect
    - AC current crowds toward outer surface of cables
    - AC resistance greater than DC resistance
    - Losses
  - Grid stability is a concern
    - Power transmission must be limited to maintain grid stability
    - Can't arbitrarily connect large sections of grid without considering stability
  - AC power transfer between asynchronous networks is not possible

High-Voltage DC Transmission

- Advantages of HVDC transmission:
  - ***Lower transmission loss***
    - No reactive power transfer
    - No skin effect
    - Less conductor required
  - ***Power flow control***
    - Independent control of real and reactive power direction and magnitude (for some HVDC architectures)
  - ***Smaller right of way (RoW) required***
    - Fewer conductors
    - Fewer towers
  - ***Less costly than AC transmission***
    - For longer lines exceeding some breakeven distance

HVDC Applications

- Long-distance bulk power transmission
  - Lower loss
  - Lower cost
  - Smaller RoW
- Power transfer between asynchronous AC grids
  - Back-to-back HVDC
  - Improves stability of each grid
  - Cascading failures will not propagate across the HVDC link
- Stabilizing AC grids
  - Power transfer within an AC network to improve stability

HVDC Applications

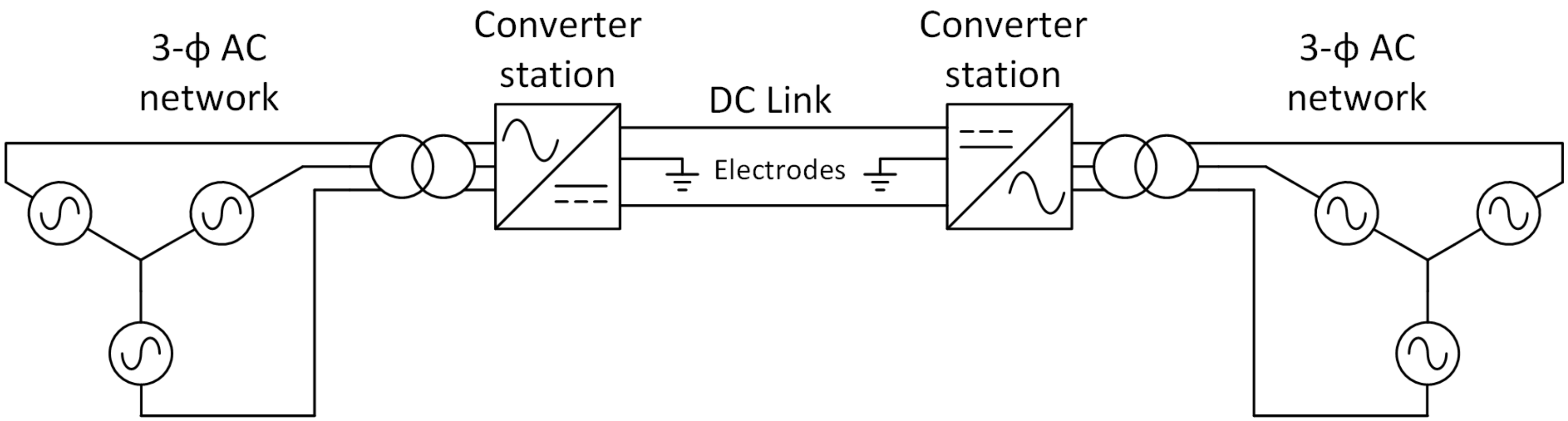
- Undersea/underground cables
  - No charging current
  - Lower loss than AC
- Integration of renewable generation sources
  - Solar/wind farms
  - Possibly distant from load centers
  - Offshore wind farms
  - Asynchronous generation

HVDC Link Configurations

HVDC System Overview

- HVDC links exist within and between 3-ϕ AC power grids
- The components of an HVDC system:
  - ***Converter stations***
    - Conversion between AC and DC
    - One at either end of a DC link
      - Collocated for back-to-back links
    - Rectifier: AC-to-DC conversion
    - Inverter: DC-to-AC conversion
  - ***Transmission lines/cables***
    - Overhead lines and towers
    - Undersea/underground cables
  - ***Electrodes***
    - Provide grounding for earth or sea return currents

HVDC System Overview

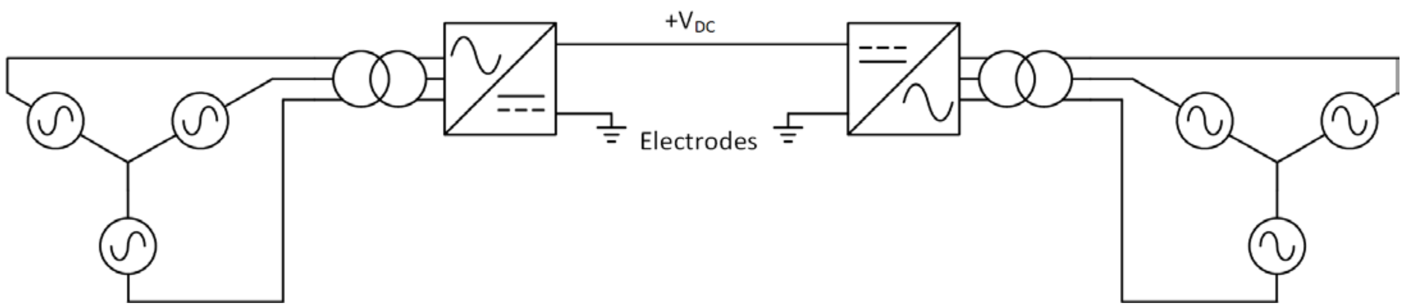


HVDC Link Configurations

- HVDC configurations differ in:
  - Number of DC poles
    - Monopolar: single DC voltage (e.g. +500 kV)
    - Bipolar: positive and negative DC voltages (e.g. $\pm$500 kV)
  - Return current path
    - Metallic
    - Ground/sea
    - None (bipolar configurations)

HVDC Link Configurations

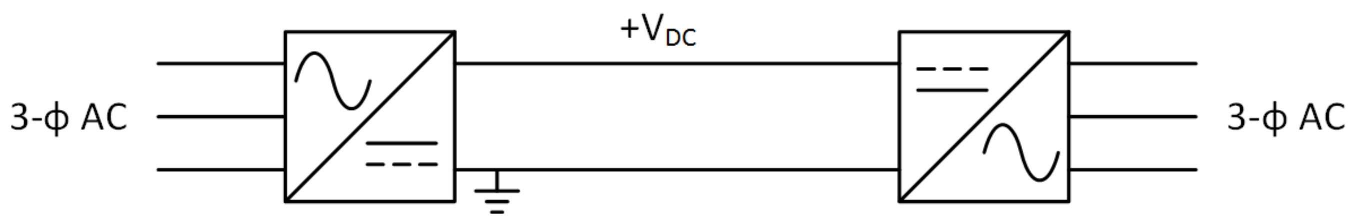
- ***Monopolar with ground/sea return path***:



  - Single HVDC line
  - Return currents flow through the earth or sea at low voltage
  - Simplest configuration
    - Electrode design is non-trivial
  - Common configuration for undersea links

HVDC Link Configurations

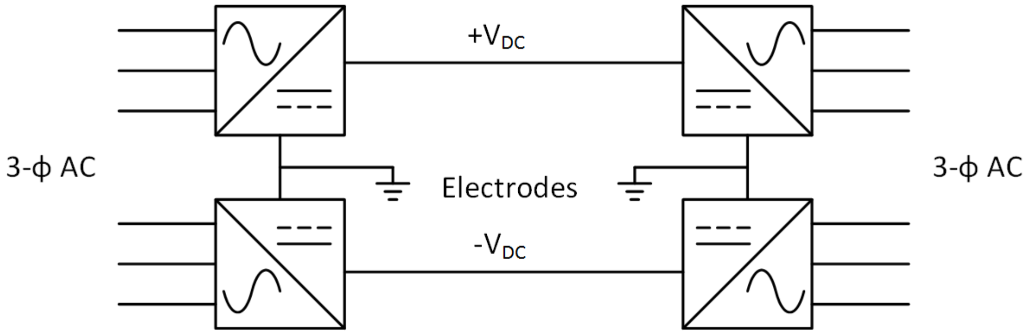
- ***Monopolar with metallic return path***:



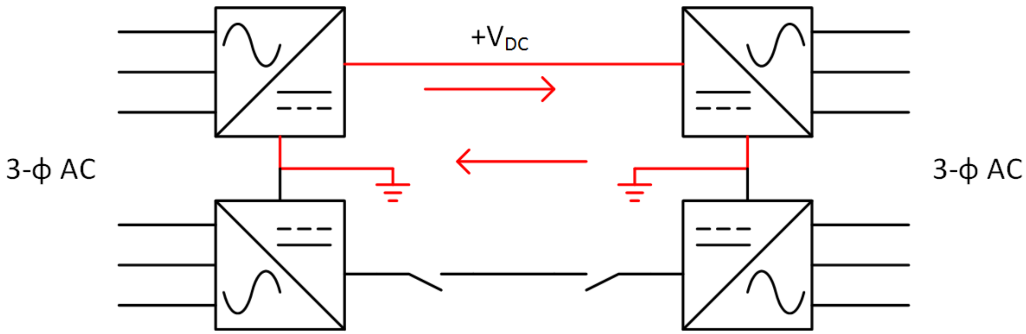
  - Dedicated metallic cable for return currents
  - When grounding electrodes and ground return current are not an option
    - Environmental concerns
    - Real estate restrictions

HVDC Link Configurations

- ***Bipolar with ground return path***:

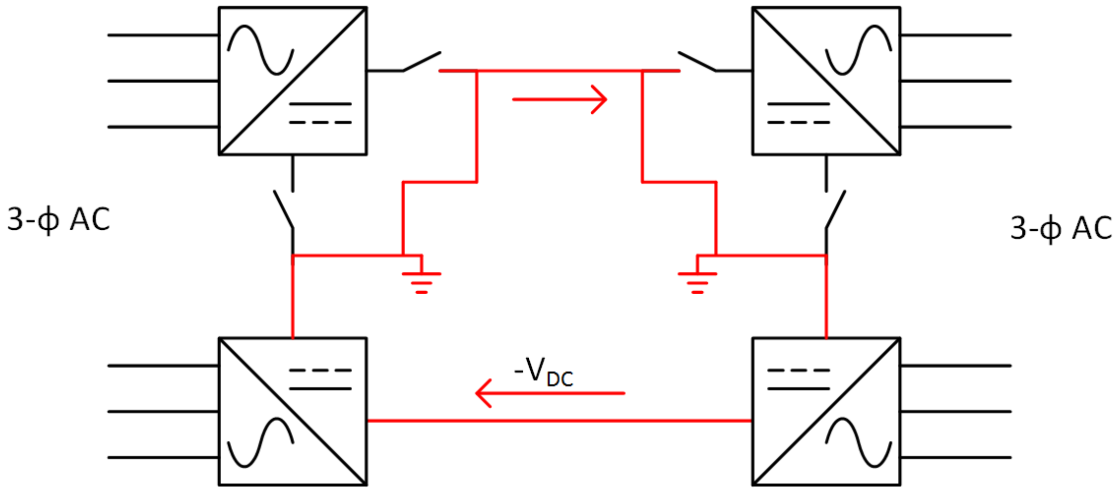


  - Positive and negative DC voltages
  - Little to no current through ground path under normal operation
  - In case of a single-pole fault, return current can flow on the ground path:



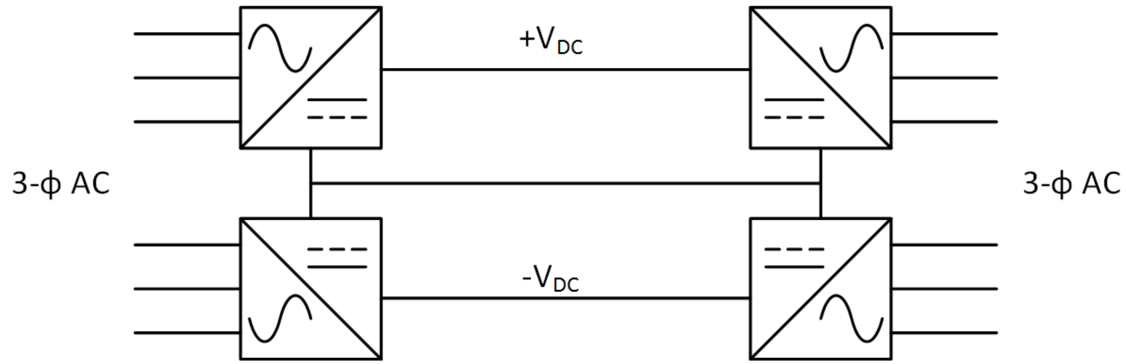
HVDC Link Configurations

- ***Bipolar with ground return path*** (cont'd):
  - In the event of a failure involving the transformer/converters of a single pole
    - Failed pole's conductors can be used as a low-voltage return path



HVDC Link Configurations

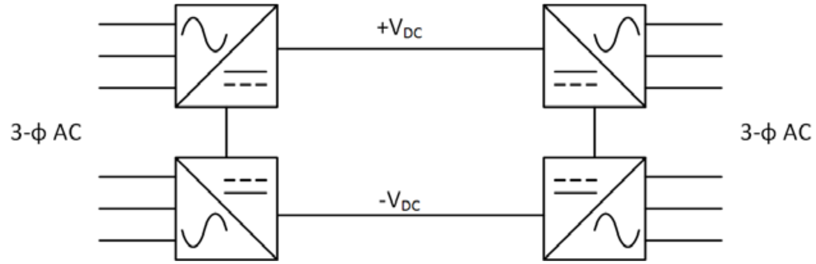
- ***Bipolar with metallic return path***:



  - Dedicated metallic cable for return currents
  - When electrodes are not a viable option
  - Little to no current in return cable under normal operation
  - Same backup mode options as bipolar w/ ground return

HVDC Link Configurations

- ***Bipolar with no dedicated return path***:



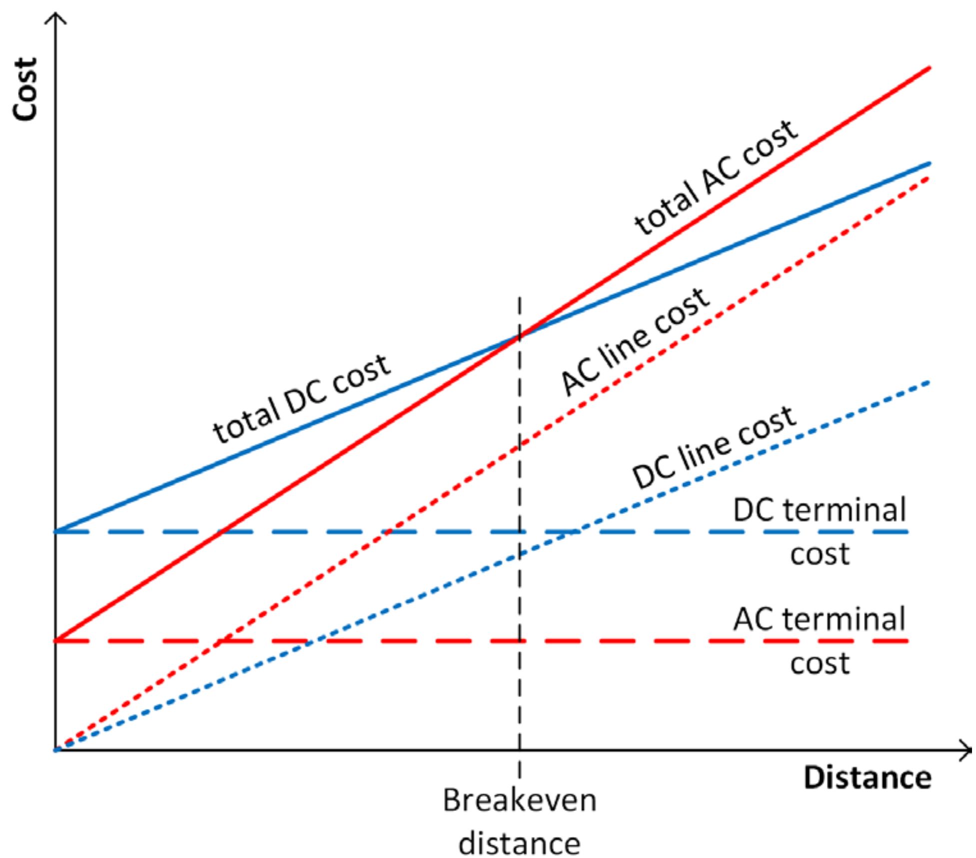
  - Least expensive bipolar configuration
  - Cable fault on either pole removes entire link from service
  - Monopolar operation is an option in the event of a single-pole converter/transformer failure

- ***Back-to-back converter***:
  - Rectifier and inverter in the same location
  - No transmission line
  - Lower voltage than for long-distance links
  - For power transfer between asynchronous AC networks

HVDC vs. AC Cost Comparison

HVDC vs. AC Cost Comparison

- For the same amount of power and loss, HVDC requires less conductor
  - Lower cost per km
- Fixed terminal station cost
  - HVDC far more costly
- Beyond some ***breakeven distance***, HVDC is more economical
  - ~600 – 800 km for overhead lines
  - ~50 km for undersea cables



HVDC System Types

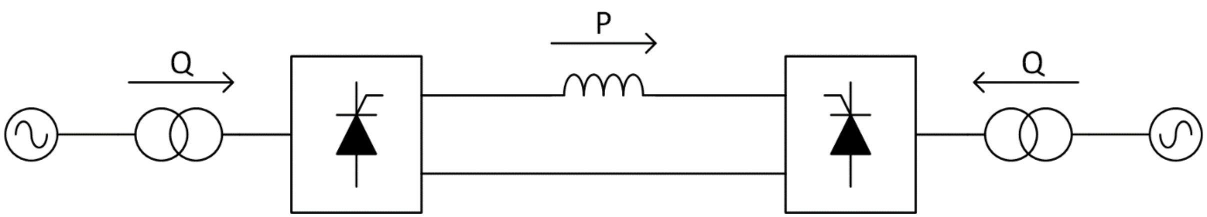
HVDC System Types

- Two basic categories of HVDC systems
  - ***Line-commutated converters***
    - Current-source converters (CSC)
  - ***Forced-commutated (or self-commutated) converters***
    - Voltage-source converters (VSC)

- Difference is in the switching devices employed and how those switches are controlled
  - Specifically, how the switches are turned off

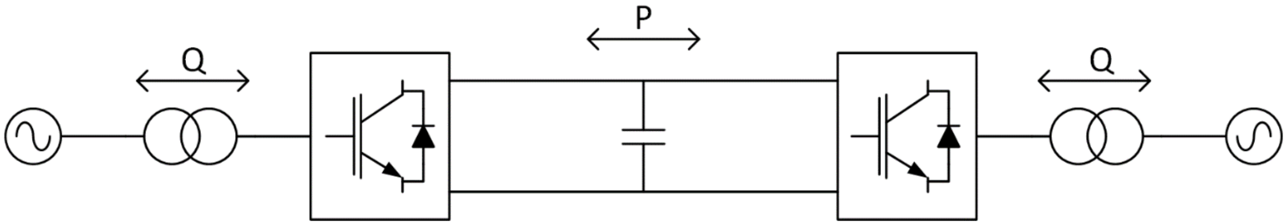
Line-Commutated Converters

- Current-source converters (CSC)
  - Converter looks like a ***current source*** to the AC grid
- **Switching devices**: thyristors
  - Previously mercury arc valves
  - Turn-on time is controlled
  - Turn-off occurs when voltage across thyristors changes polarity (goes negative)
  - Operation requires active generation in AC grid
- Typical loss: <1% per converter station
- **Power flow**
  - Converters consume reactive power
  - Real power flow along DC link in one direction only



Self-Commutated Converters

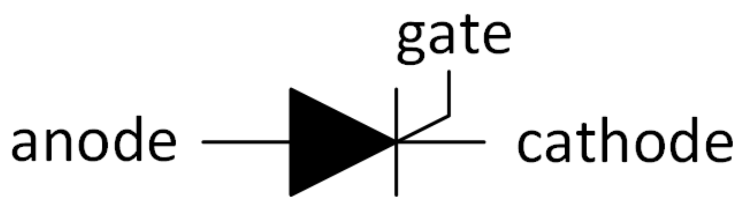
- Voltage-source converters (VSC)
  - Converter looks like a ***voltage source*** to the AC grid
- **Switching devices**: typically insulated gate bipolar transistors (IGBTs)
  - Turn-on and turn-off is controlled by a control signal
  - Capable of operating connected to AC grid with only passive loads
  - Can provide black start capability
- Typical loss: 1% - 3% per converter (varies with topology)
- **Power flow**
  - Independent control of real and reactive power



Line-Commutated Converters

Line-Commutated Converters

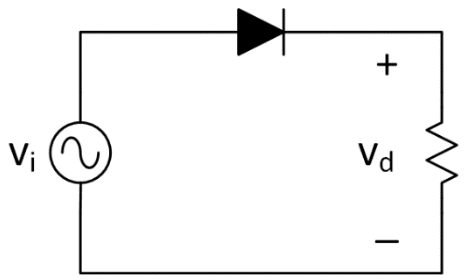
- Line-commutated converters
  - Most common type of HVDC system currently in operation
  - Converters use thyristors as switching elements
- ***Thyristor***

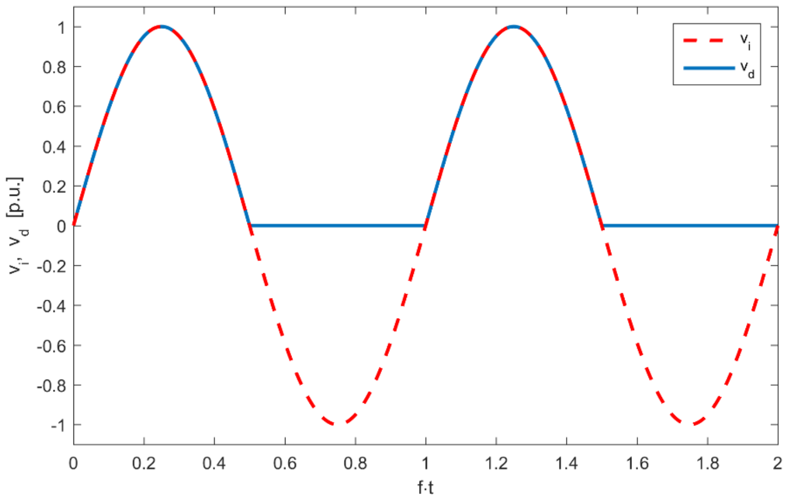


  - Like diodes, thyristors block current in the reverse (cathode-to-anode) direction
  - Unlike diodes, thyristors also block forward current until turned on with a control signal applied to the gate terminal

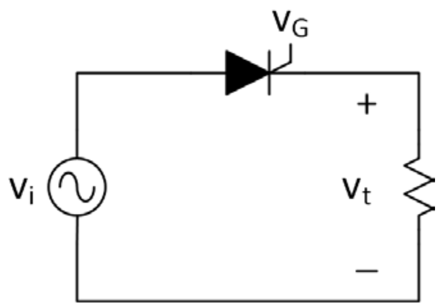
Thyristors

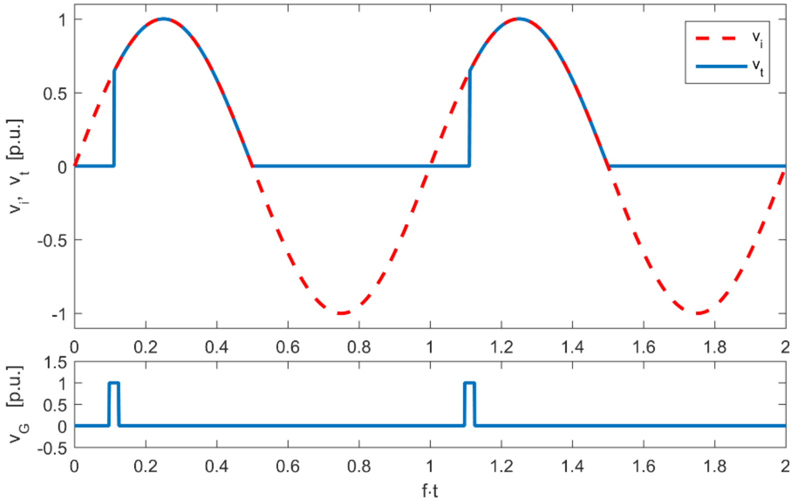
- Diode half-wave rectifier





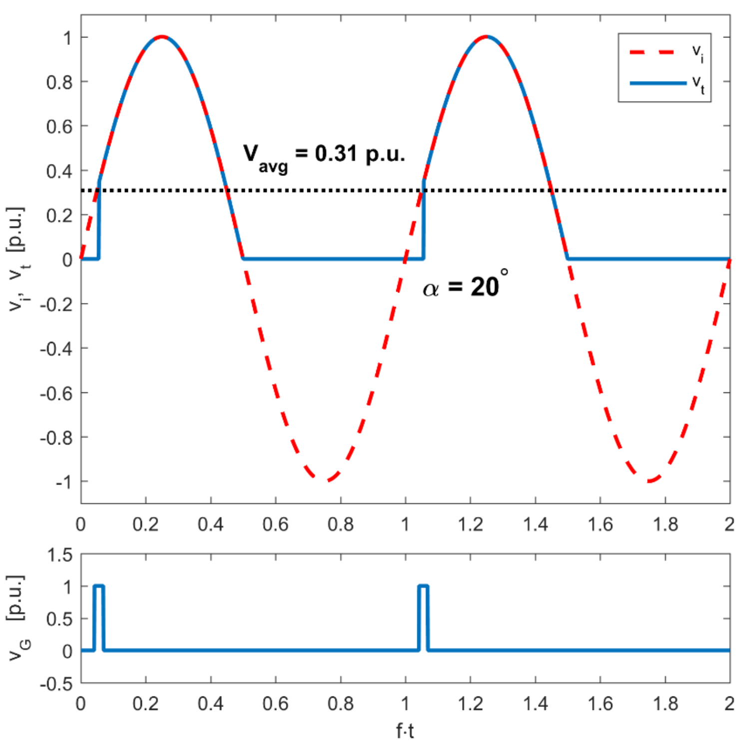
- Thyristor half-wave rectifier

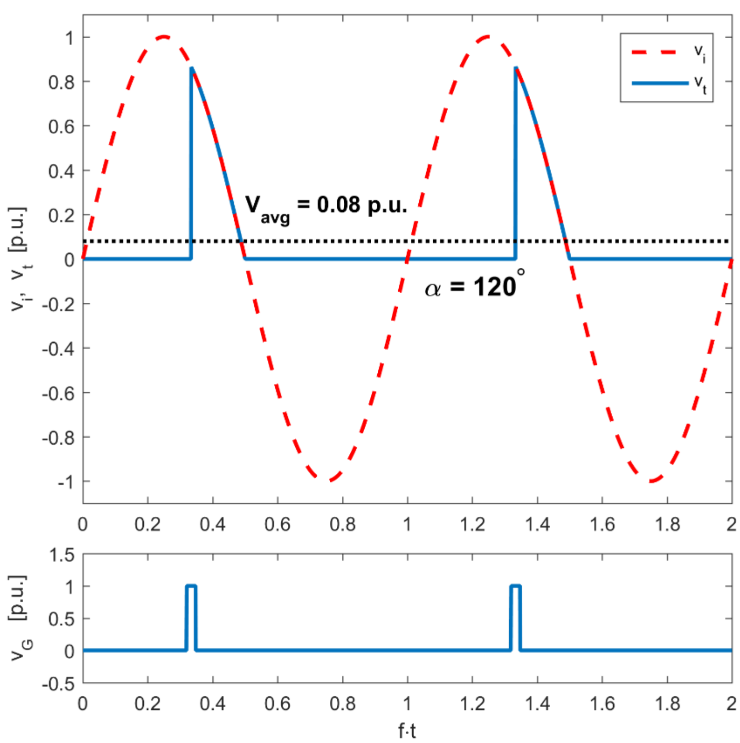




Delay Angle

- Thyristor turn on time can be delayed past the point of natural conduction by a ***delay angle***, α
  - Average output voltage controlled by α

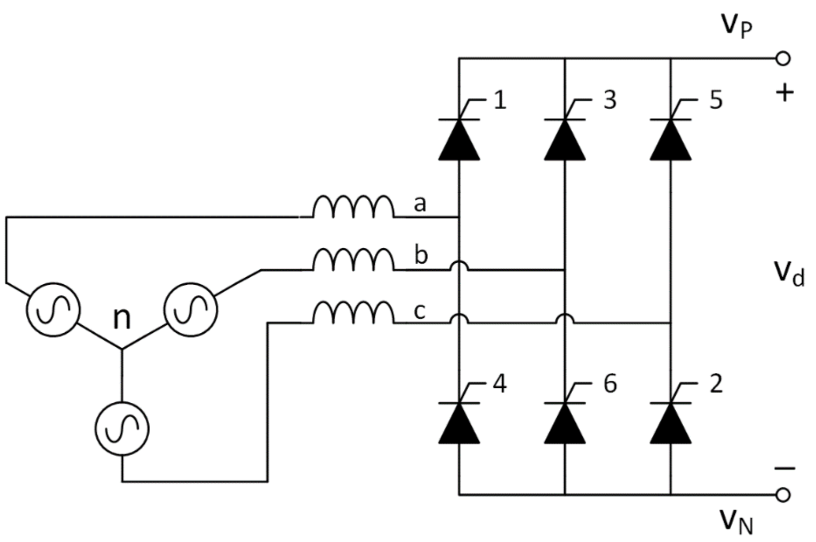




Three-Phase Full-Bridge Converters

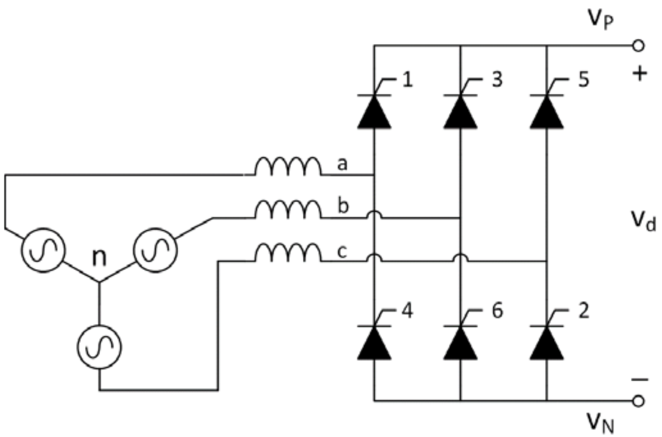
- Converter stations use thyristors arranged in full-bridge configurations
- ***Six-pulse thyristor converter***:
  - Commutation occurs every 60°
  - Thyristors numbered in order of conduction
  - DC output voltage:

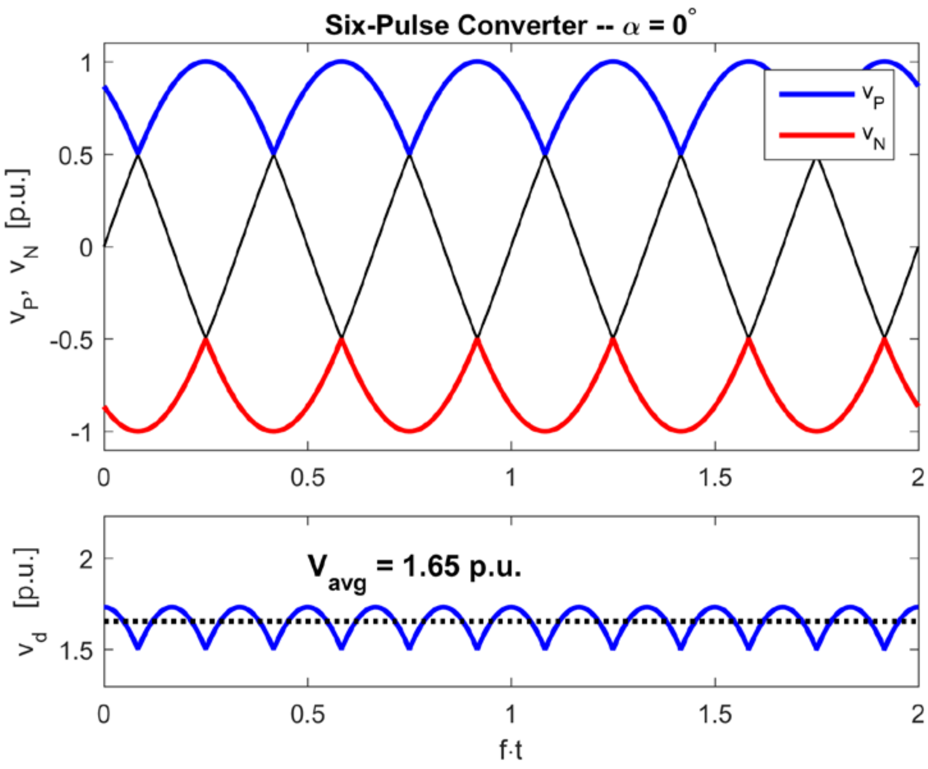
$$v_d = v_{Pn} - v_{Nn}$$



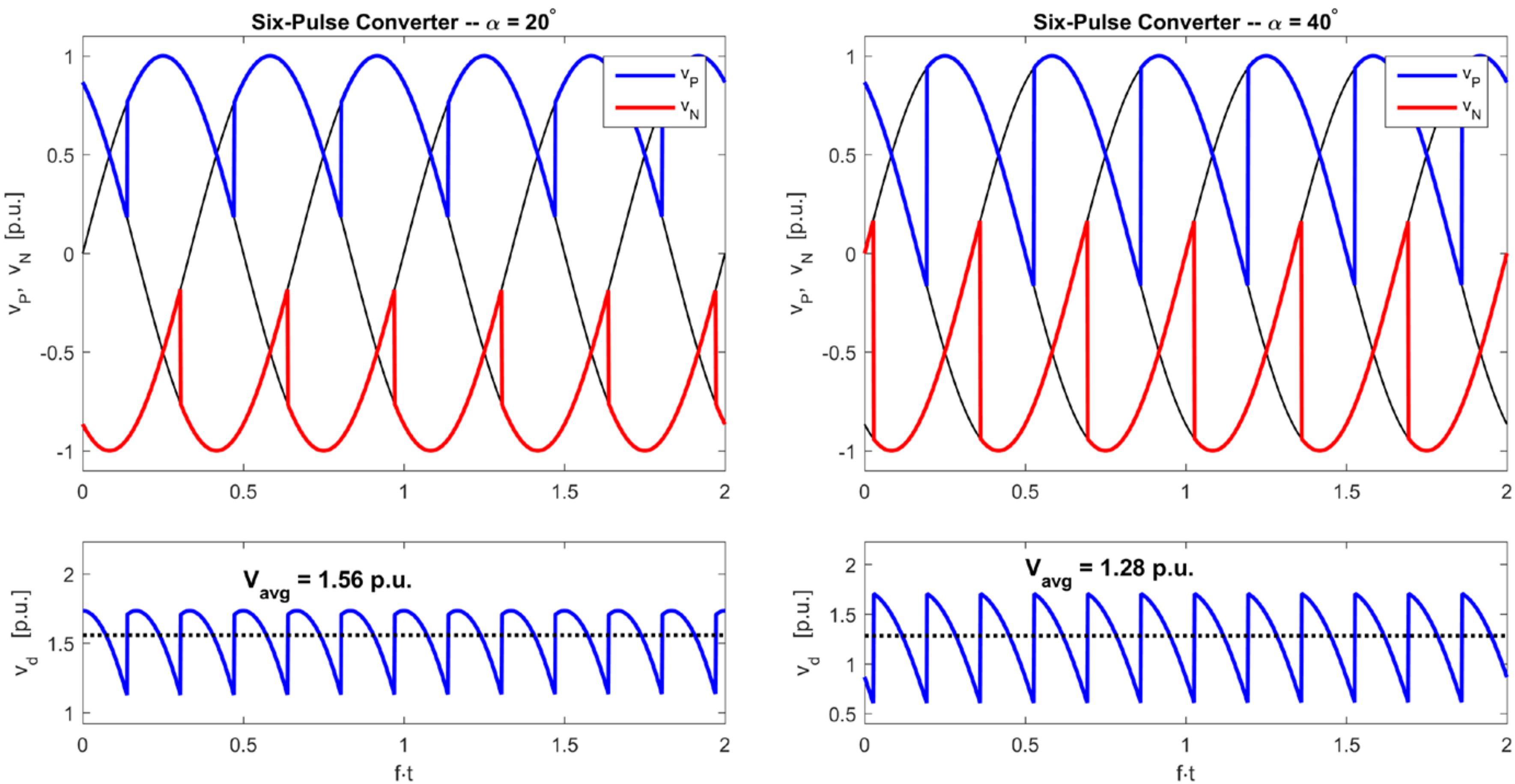
Six-Pulse Converter

- Turn-on time delayed by ***delay angle***, α, past the point of natural commutation
  - Maximum average DC output for $\alpha = 0°$
  - Average DC output is negative for $\alpha > 90°$



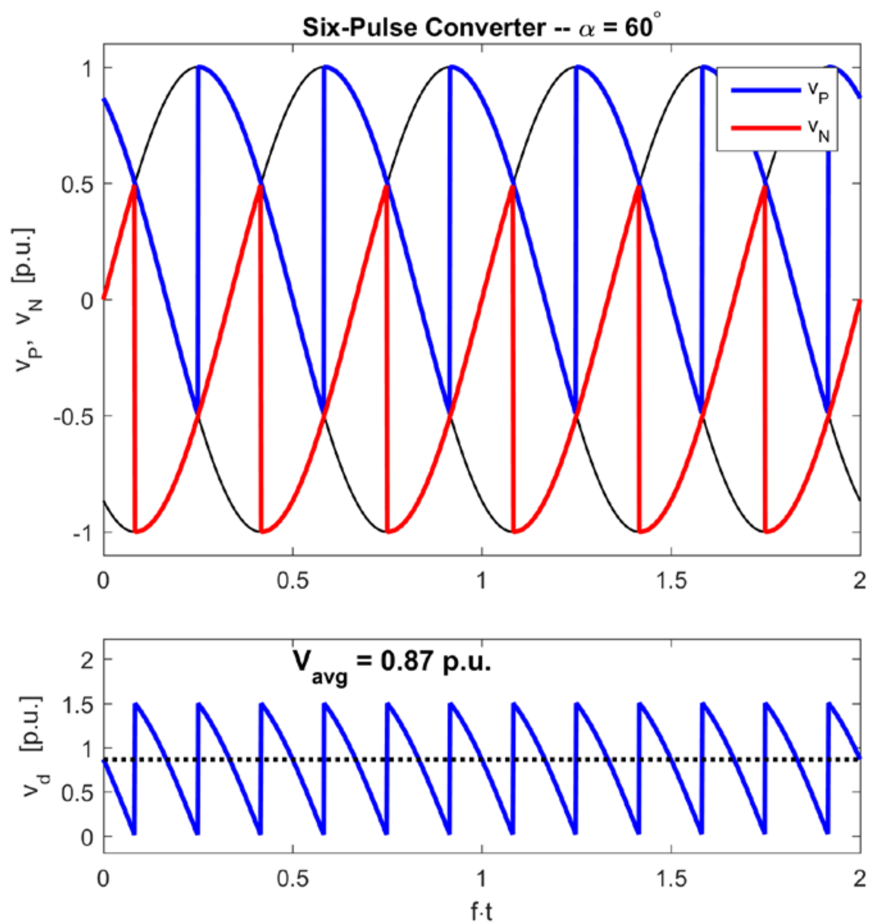


Six-Pulse Converter



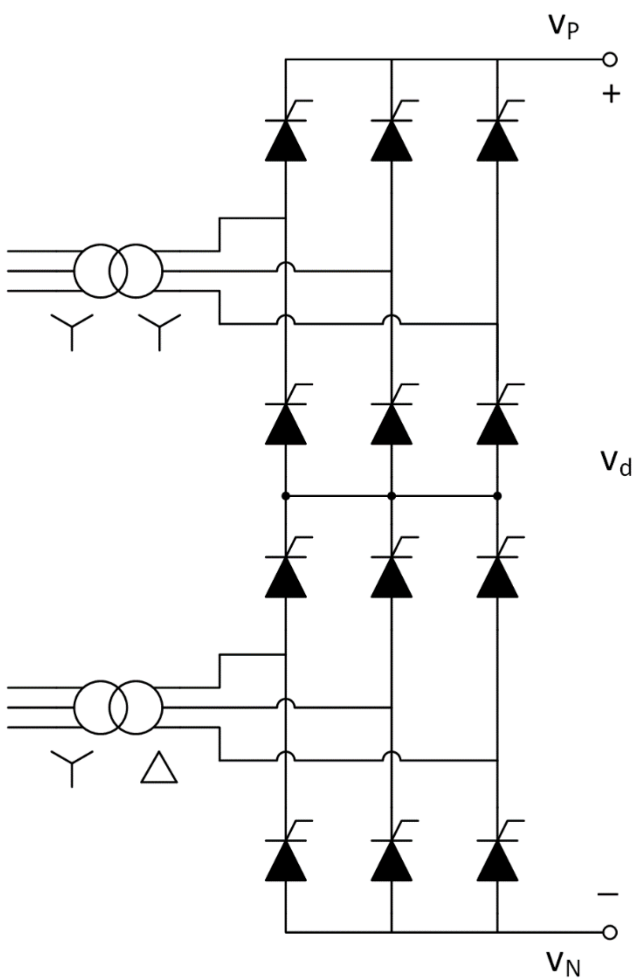
Six-Pulse Converter

- Converter output, v_d, is clearly not pure DC
  - Six pulses per period
  - Significant ***harmonics*** injected onto the AC grid
  - ***AC filtering*** required to reduce harmonics



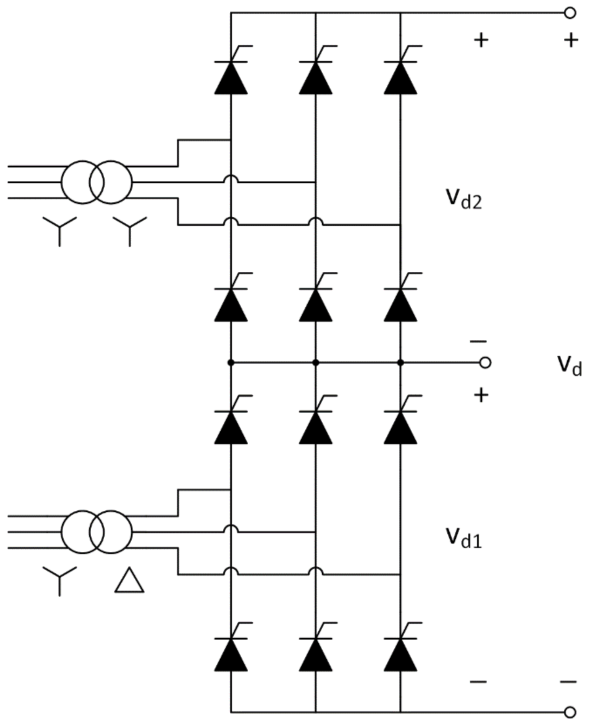
Twelve-Pulse Converter

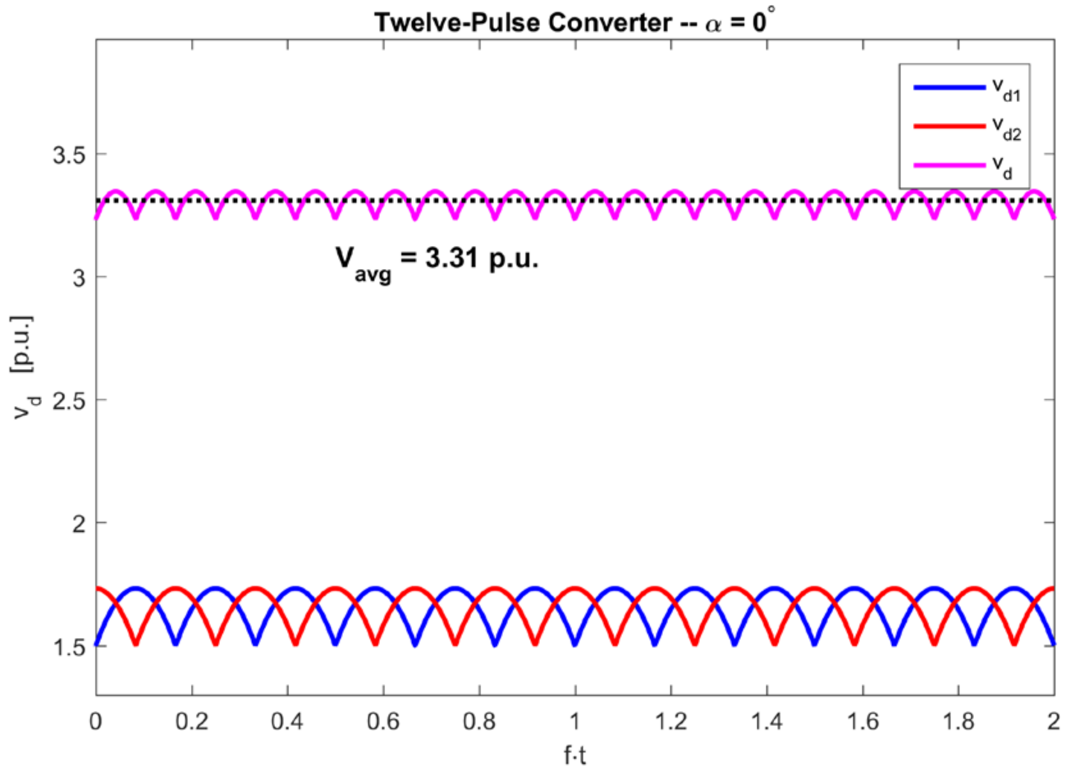
- ***Twelve-pulse converter***
  - Two six-pulse bridges connected in series
  - Three-phase input to one bridge is phase shifted 30° relative to the input of the other
    - Y/Y and Y/Δ transformers
  - Commutation occurs every 30°



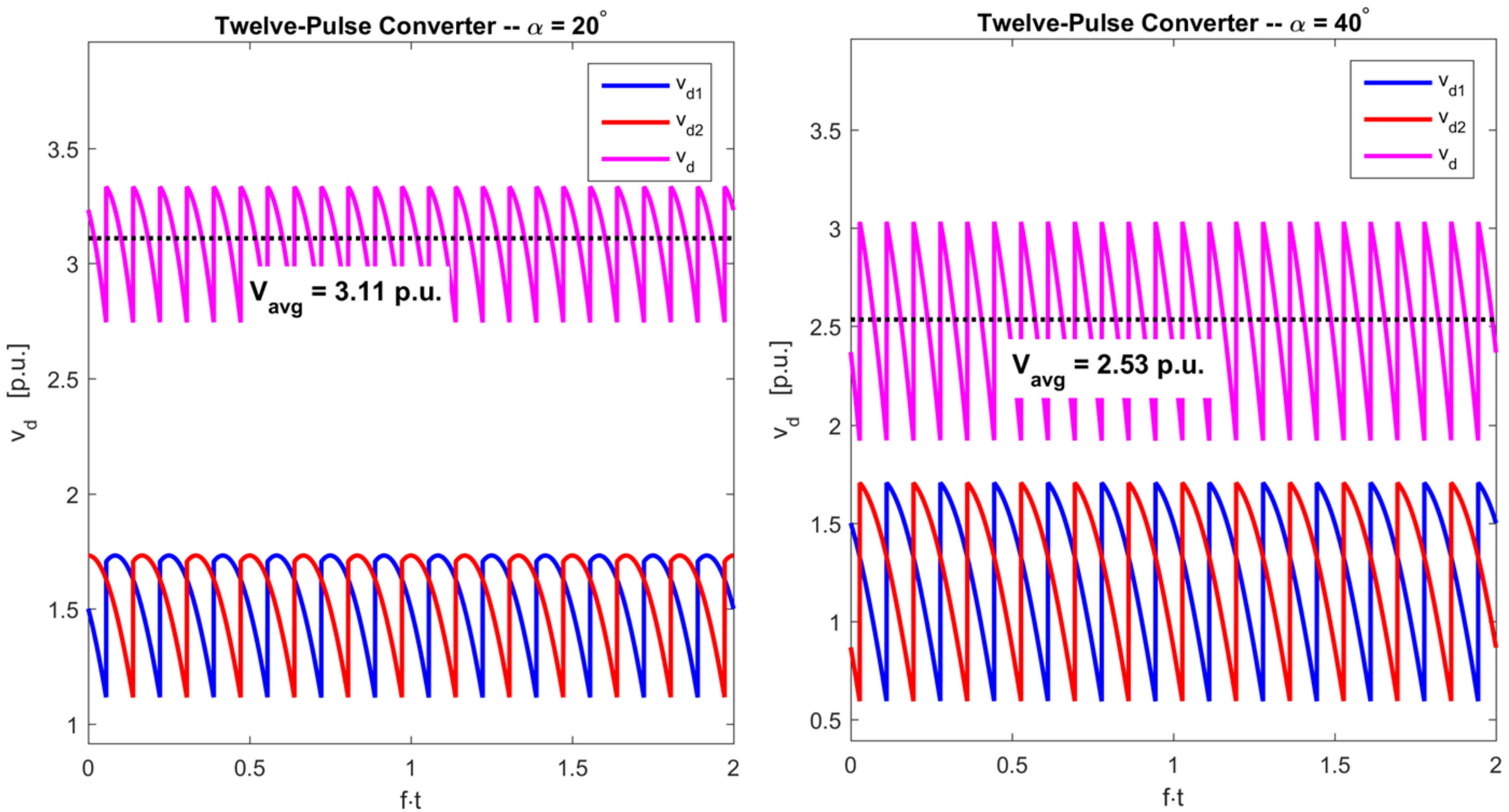
Twelve-Pulse Converter

- Now, 12 pulses per period
  - Harmonics are greatly reduced
  - AC filtering requirements are lessened



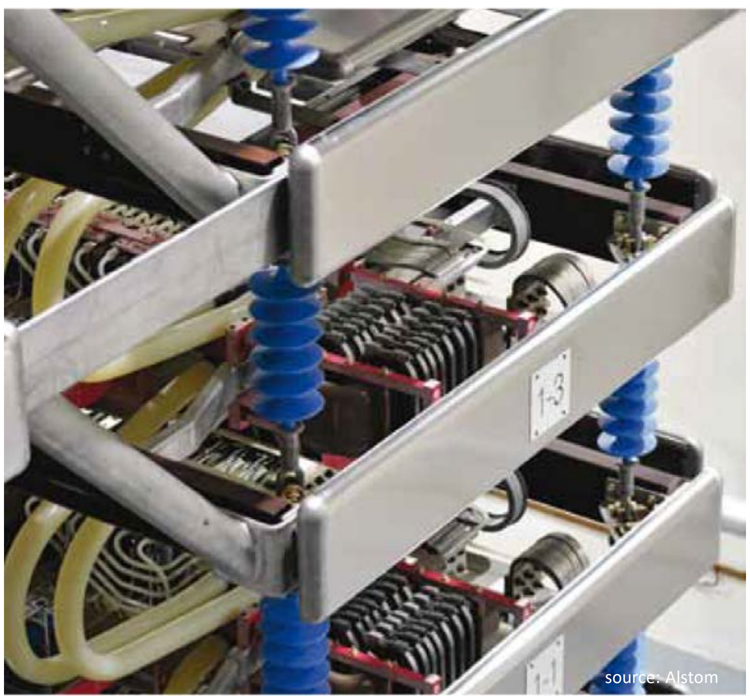


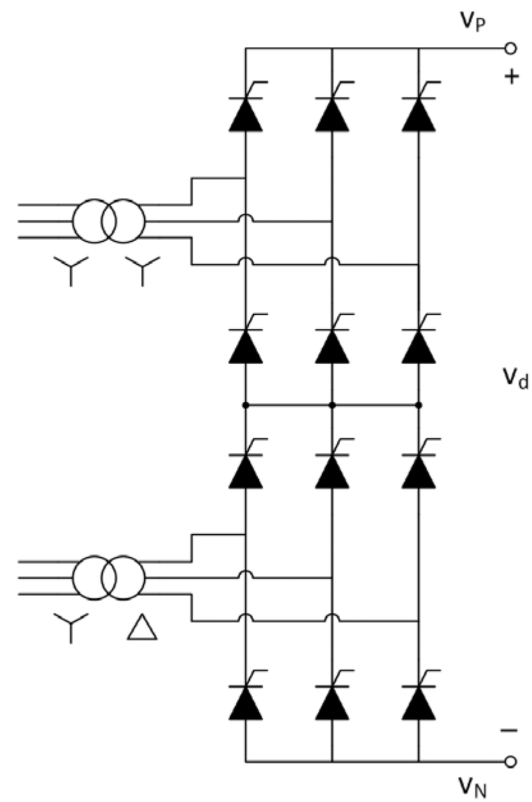
Twelve-Pulse Converter



Thyristor Valves

- Each thyristor shown in the bridge schematics is really many series-connected thyristors
  - Necessary to withstand high voltages
  - Each group of thyristors called a ***valve***



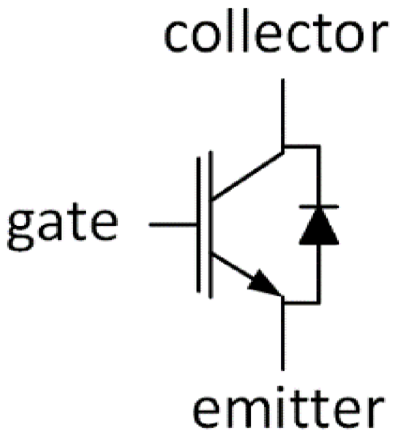


Voltage Source Converters

Voltage Source Converters

- ***VSC HVDC*** systems use switching devices that can be turned on and off
  - **IGBT**: insulated-gate bipolar transistor
  - **GTO**: gate-turn-off thyristor
  - **IGCT**: insulated gate commutated thyristor

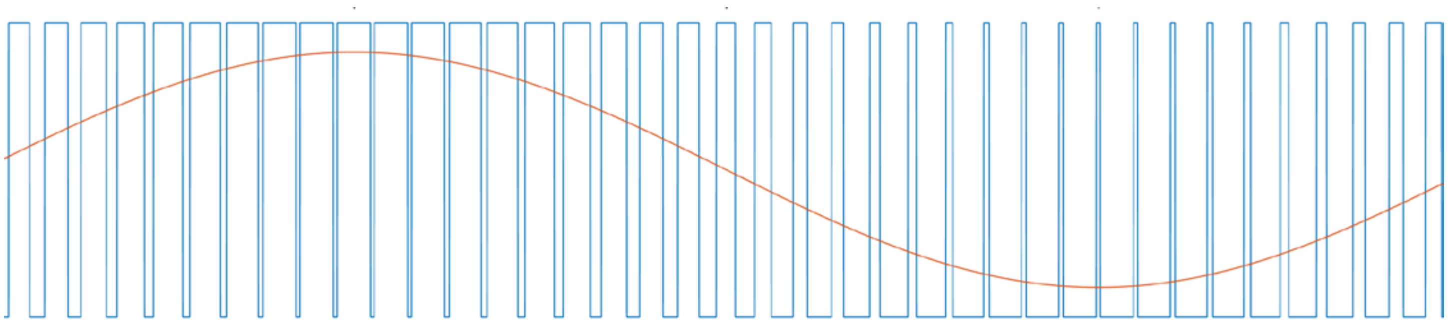
- Most commonly used devices are ***IGBTs*** with anti-parallel free-wheeling diodes



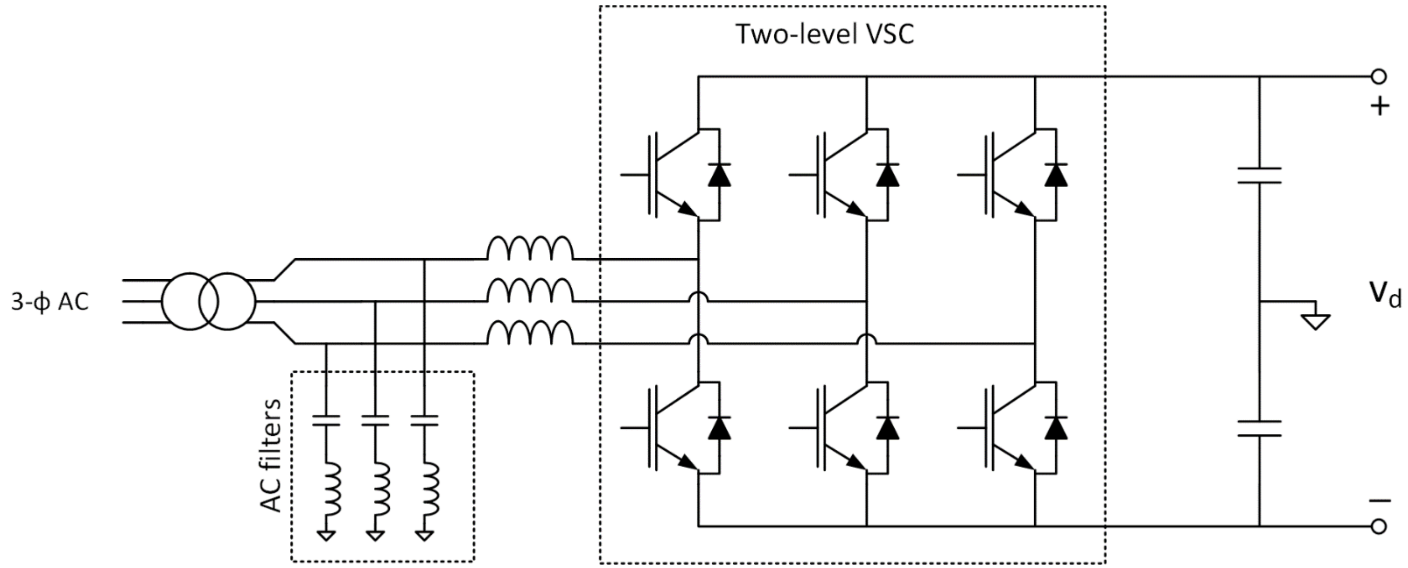
Voltage Source Converters

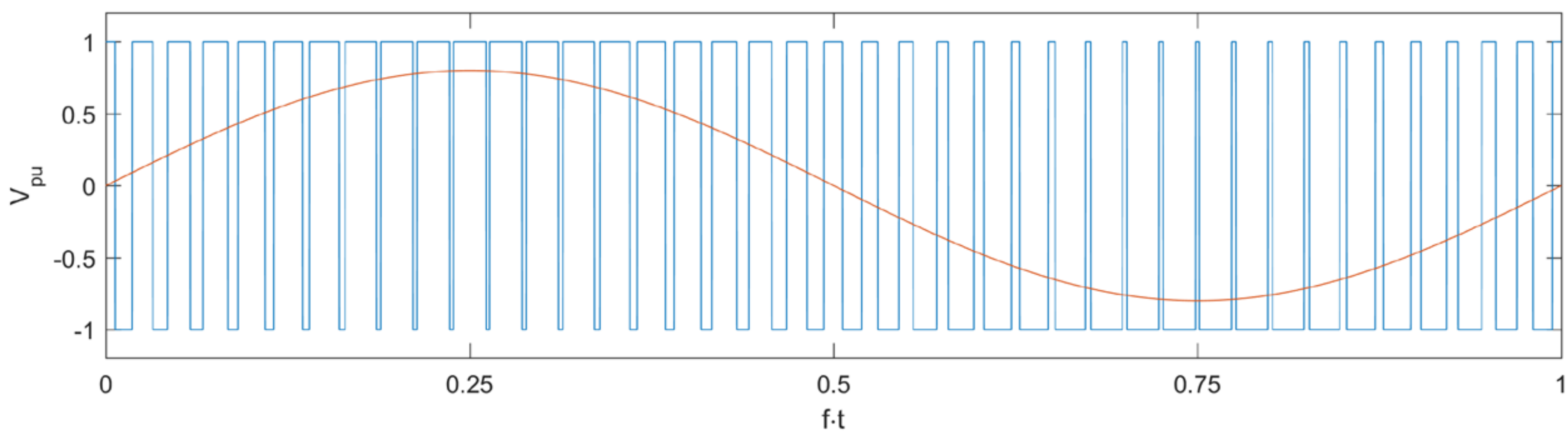
- **VSC configurations**:
  - Two-level converter
  - Multi-level converter
  - Modular multi-level converter (MMC)

- Operation of two-level and multi-level converter is based on the principle of ***pulse-width modulation*** (***PWM***)
  - Switches open and close between three-phase AC and DC poles at a frequency well above the power line frequency
  - Duration that switches are connected to DC voltage (pulse width) is varied
  - Average output voltage approximates sinusoids at the line frequency



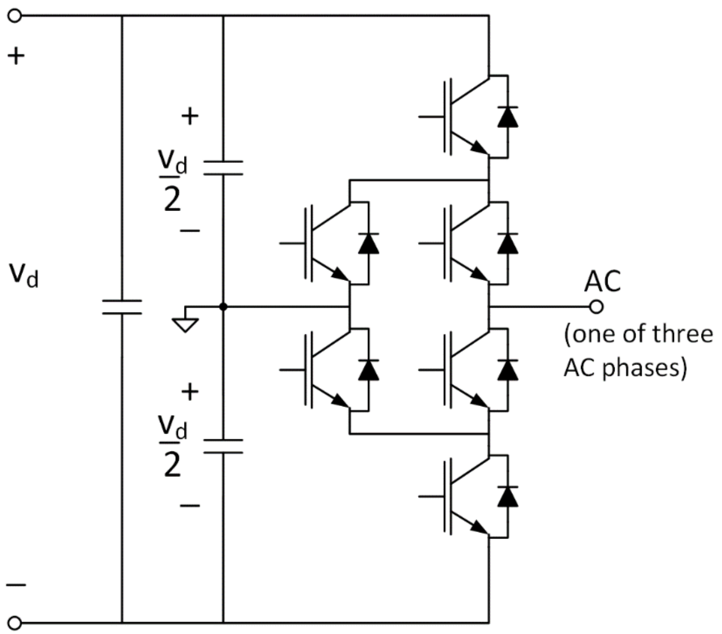
Two-Level Converter

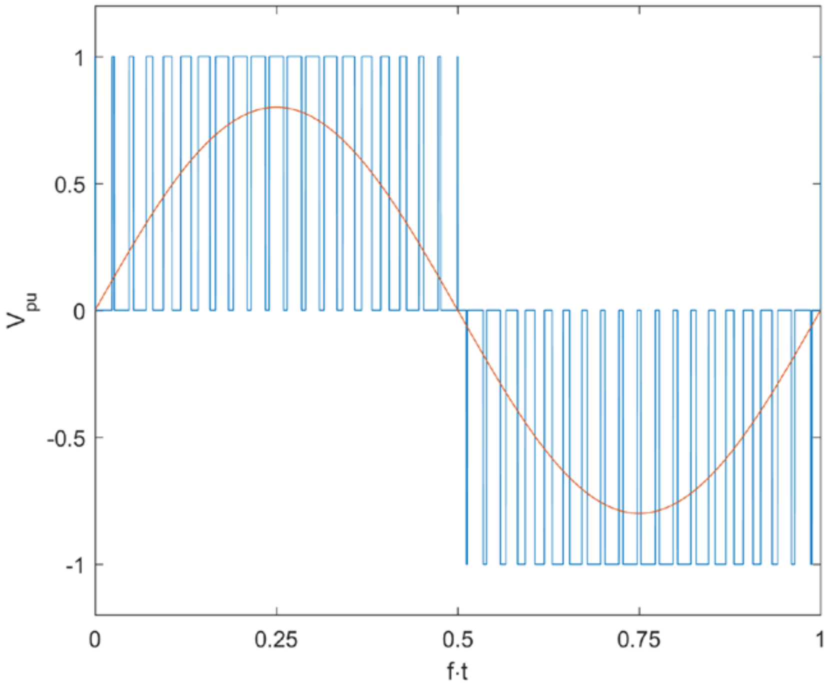




Three-Level Converter

- Similar to two-level VSC, but now PWM voltage switches between three levels
  - Closer approximation of a sinusoid
  - Harmonics are reduced
  - Filtering requirements are reduced



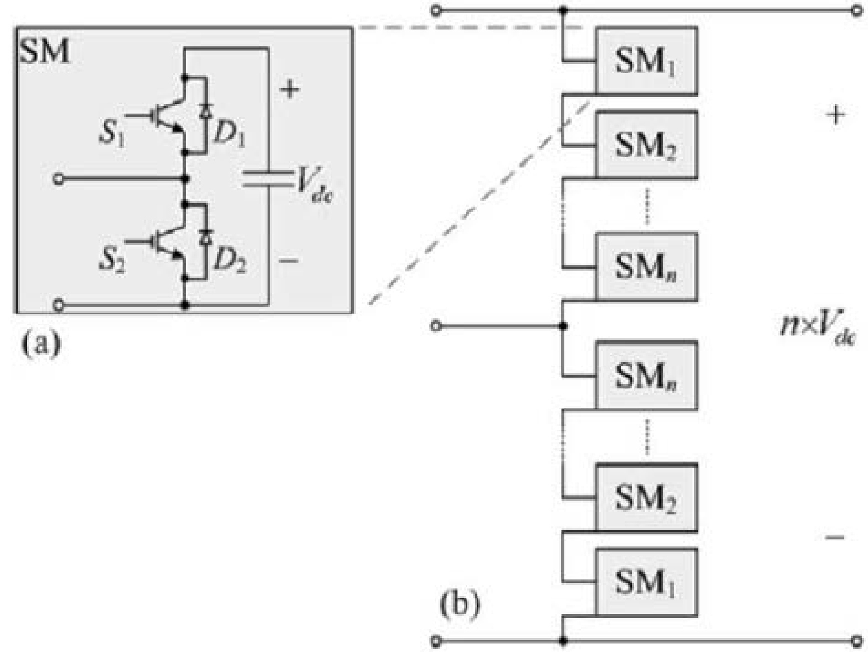


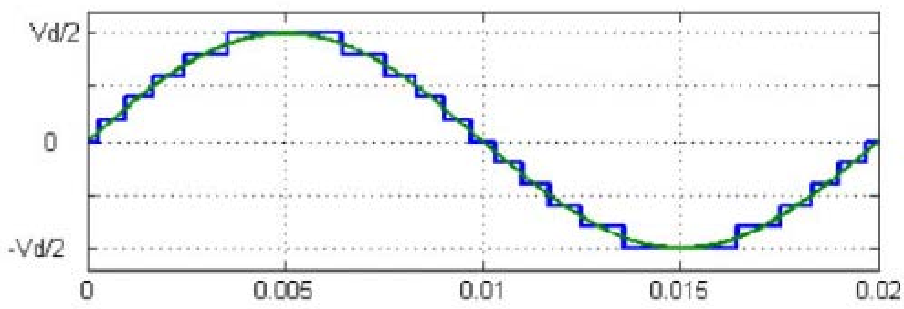
Modular Multilevel Converter

- ***Modular multilevel converter*** (***MMC***)
  - Six valves, like two-level converter
    - One connecting each AC phase to each DC voltage
  - Valves act as individual voltage sources
    - Not binary switches
    - AC synthesized with many (hundreds) voltage levels
  - ***PWM is not used***
    - Lower switching losses
  - ***Very low harmonics***
    - Filtering often unnecessary
    - Much smaller converter station footprint
  - Complex control system requirements
  - Common architecture for new HVDC projects
    - E.g. Trans Bay Cable, Pittsburg to San Francisco, CA

Modular Multilevel Converter

- Multiple ***submodules*** connected in series
  - Typically hundreds
  - One for each voltage level
- Two states for each:
  - Capacitor connected in series with the output
    - Stored voltage added to the output
  - Capacitor bypassed
    - No voltage added to the output





source: *An Overview Introduction of VSC-HVDC: State-of-art and Potential Applications in Electric Power Systems*; Feng Wang, Tuan Le, Anders Mannikoff, Anders Bergman; Cigrè International Symposium, Bologna, Italy, Sept. 2011.

HVDC Converter Stations

Valve Hall

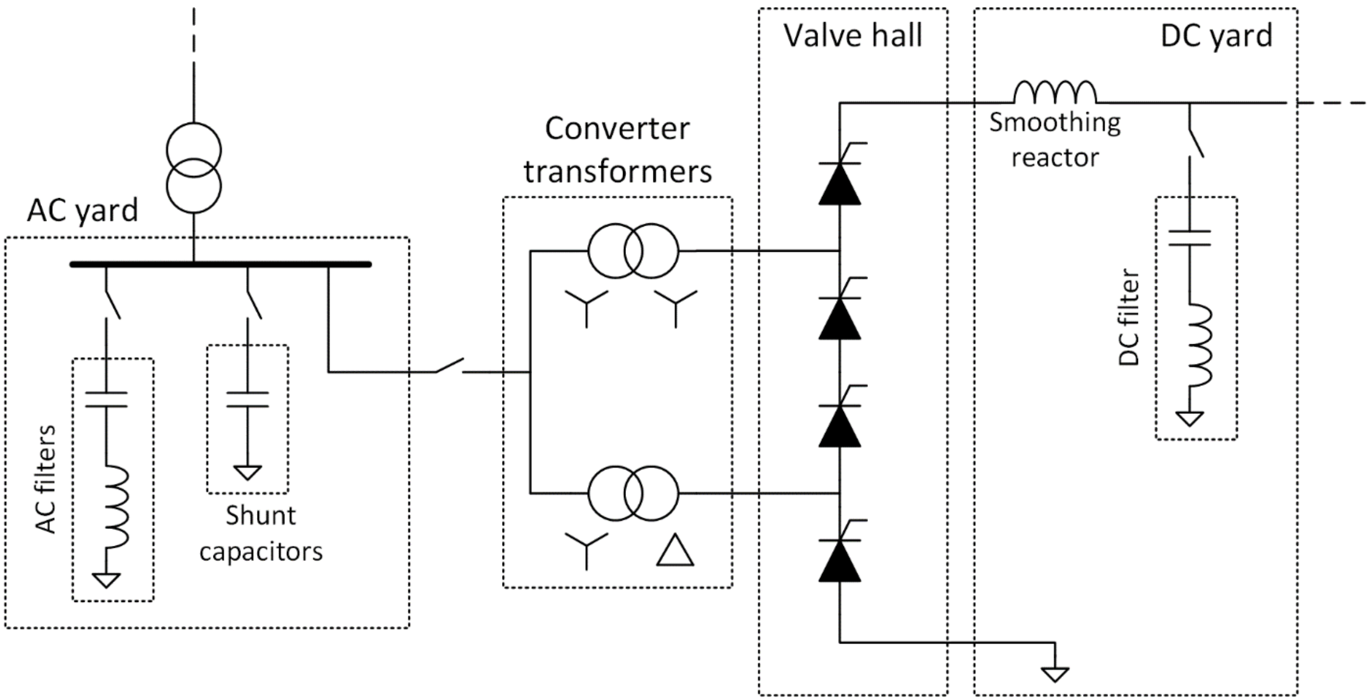
- Thyristor valve units
  - Installed indoors – ***valve hall***
  - Valves are suspended from the ceiling
    - Lower voltage near the ceiling
    - Highest voltages at the bottom
  - Air insulated
  - Water cooled

Converter Transformers

- Converter transformers are located outside
  - Large wall bushings bring AC power into the valve hall

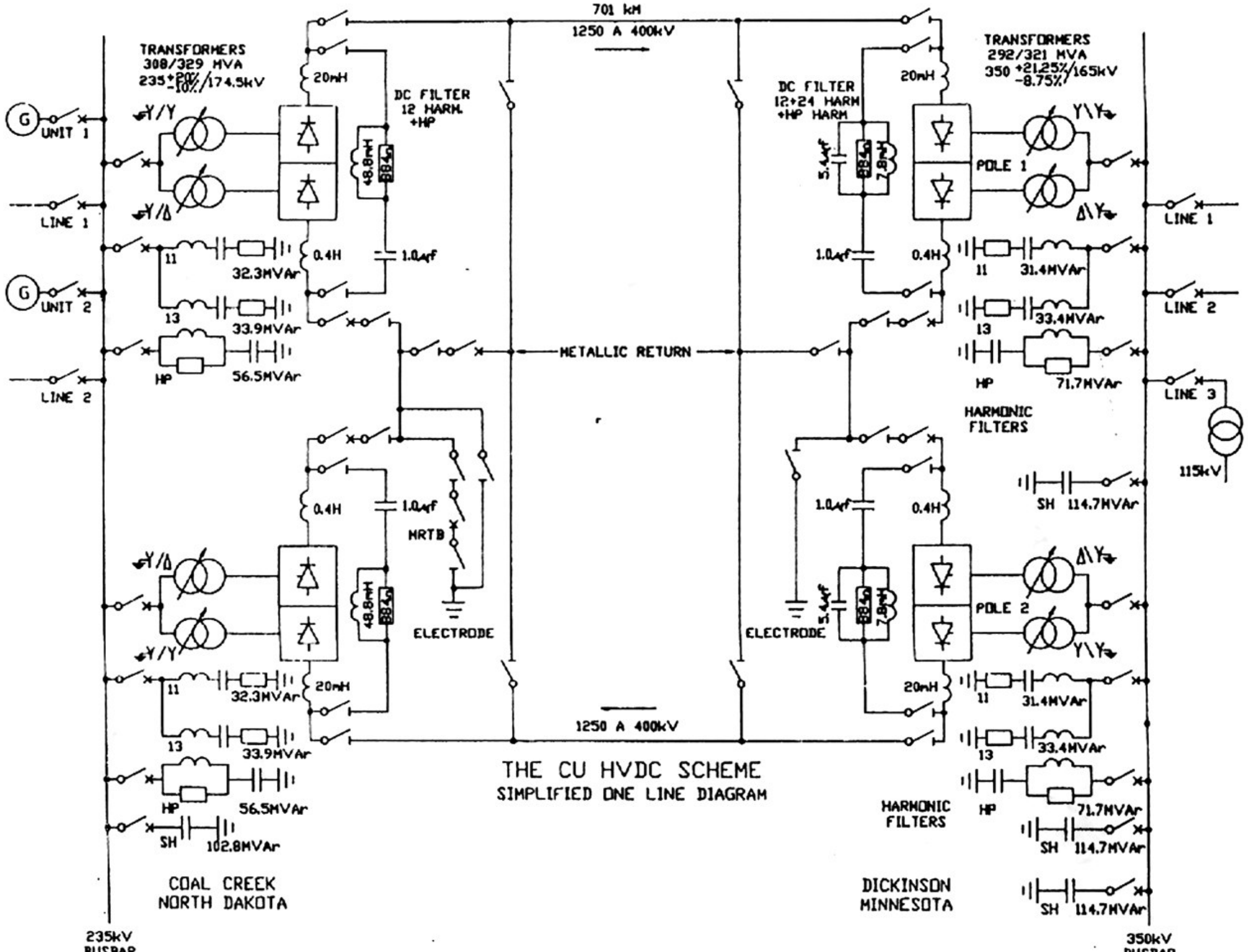
Converter Station

- Simplified converter station one-line for single HVDC pole:



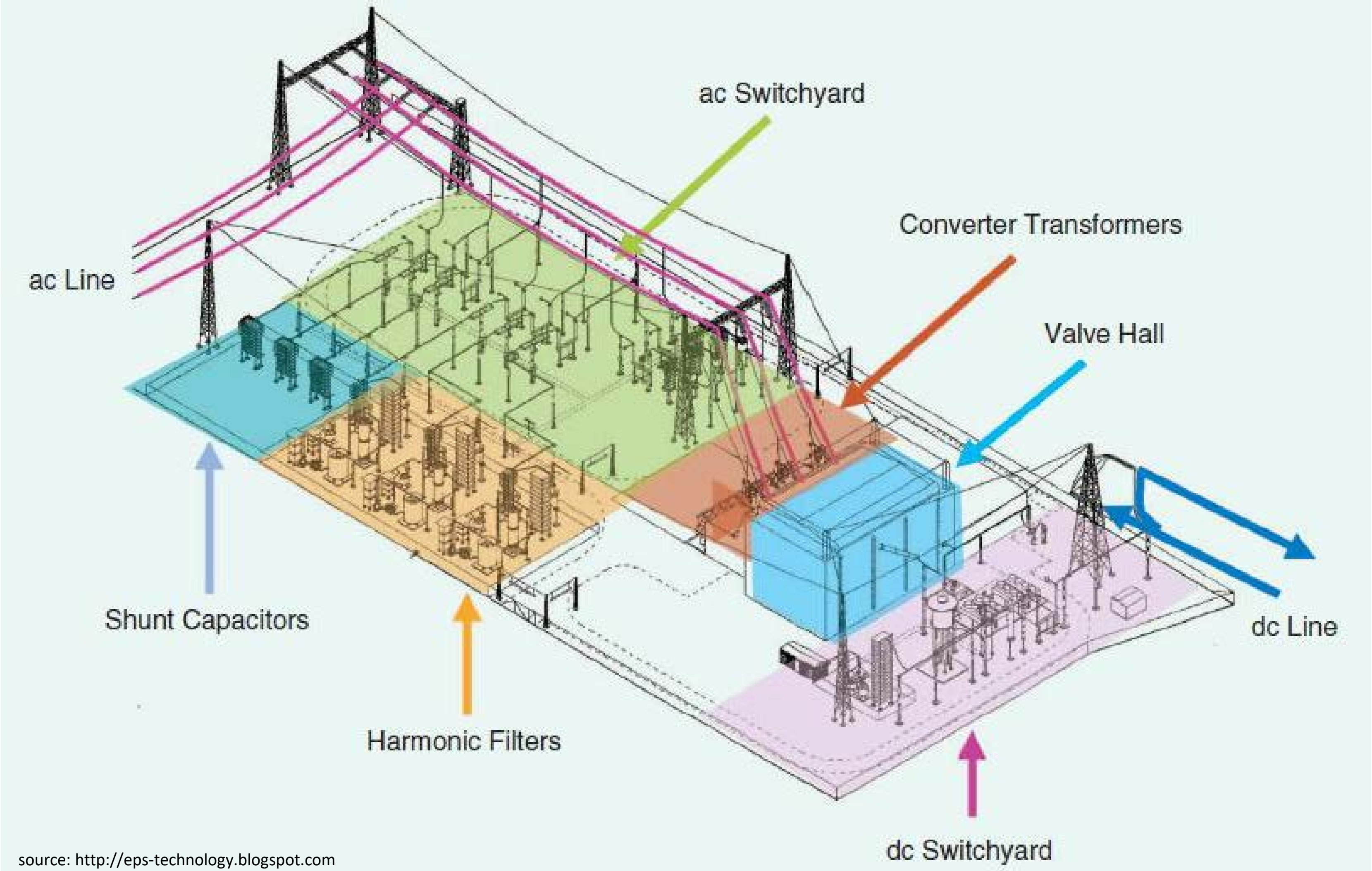
- Replicated for bipolar configuration

Converter Station



source: Electric Power Systems, A First Course; Ned Mohan; John Wiley & Sons; Great River Energy

Station Layout – Single DC Pole



source: http://eps-technology.blogspot.com

Example HVDC Projects

Pacific DC Intertie

- The Dalles, OR to Sylmar, CA
  - Columbia River hydropower to LA
- Length: 1,362 km
- Capacity: 3100 MW
  - ~50% of LA's peak load
- Bipolar w/ ground return
  - ±500 kV
- Twelve-pulse thyristor converters

Pacific DC Intertie

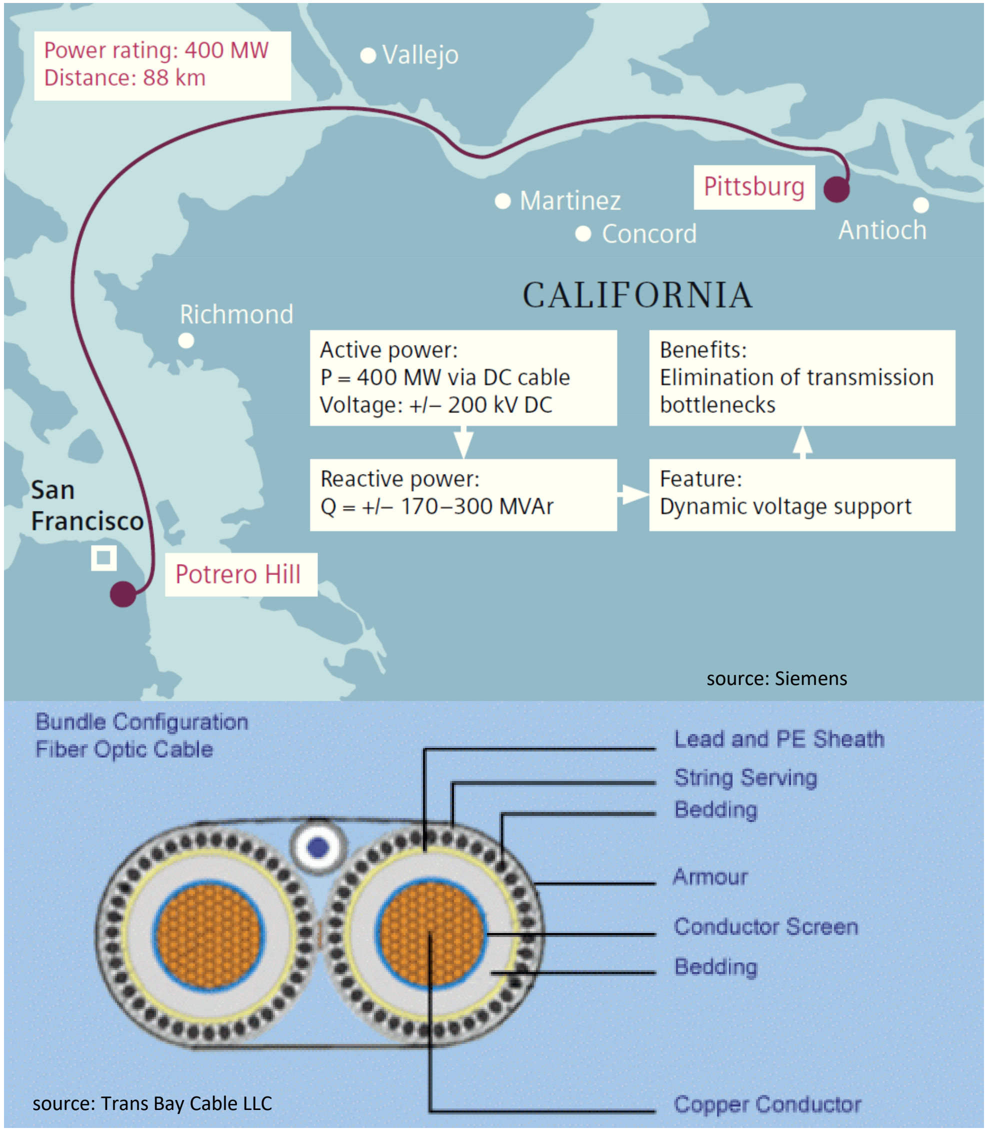
- Pacific DC Intertie towers south of Prineville

Rio Madeira, Brazil

- Amazon basin to Sao Paulo
  - Hydropower to coastal cities
- Length: 2,375 km
  - World's longest
- Capacity: 6300 MW
- Bipolar w/ ground return
  - $\pm$600 kV
- Twelve-pulse thyristor converters

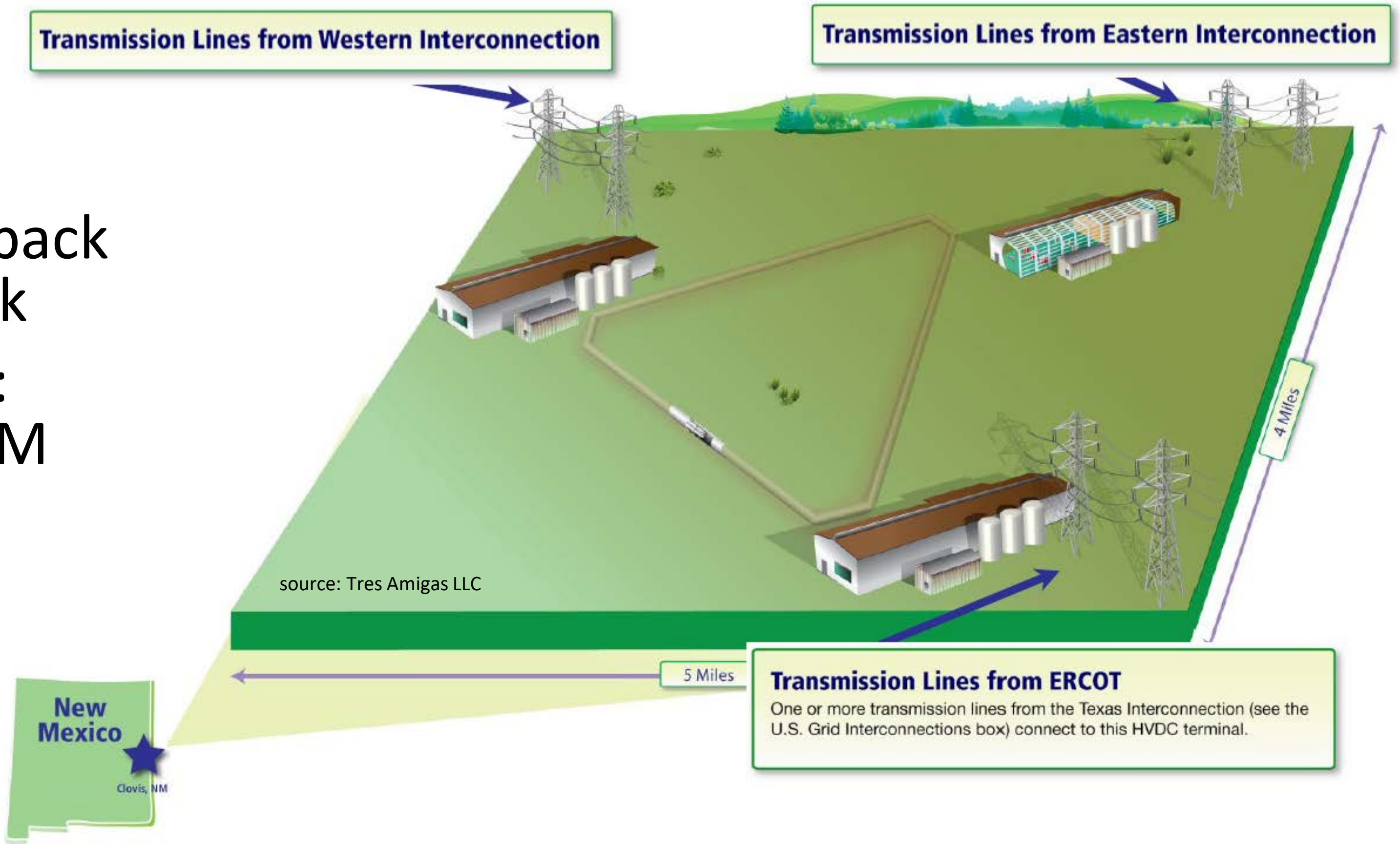
Trans Bay Cable

- Pittsburg, CA to San Francisco
  - Additional power to geographically-isolated San Francisco
- Length: 88 km
  - Under the SF Bay
- Capacity: 800 MW
- Bipolar with metallic return
  - ±200 kV
- MMC VSC



Tres Amigas – B2B Converter

- Back-to-back HVDC link
- Location: Clovis, NM



source: Tres Amigas LLC

- Back-to-back converters will connect Eastern, Western, and Texas Interconnections

Tres Amigas – B2B Converter

- HVDC converter stations
  - Connected by three 5 GW DC links
  - Scalable to 30 GW
- High temperature superconducting DC cable
  - Underground ring configuration
- Converter station may also include 5 MW battery storage for voltage and frequency regulation
- Project still in planning phases
  - System design/timeline still uncertain